SYNCHRONIZATION OF A PILOT ASSISTED CHANNEL ESTIMATION ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING SYSTEM

Field of the Invention

[0001] The present invention relates generally to synchronization for orthogonal frequency division multiplexing (OFDM), and more particularly to time-frequency compensated synchronization for pilot assisted channel estimation OFDM communication systems.

Background

[0002] A pilot assisted channel estimation OFDM system has a transmitter that sends predetermined pilot symbols in a set of dedicated time and frequency pilot points for receipt by a receiver. The receiver uses the pilot symbols to help decode the signal. The pilot assisted channel estimation OFDM is sensitive to time and frequency synchronization errors that cause baseband phase rotations in the channel. The phase rotations reduce channel time and frequency coherence, thereby increasing the interpolation error of pilot assisted channel estimations. The interpolation error can dramatically degrade the channel estimation of a single path channel system and is even more pronounced in multiple path channel systems.

[0003] Various methods are presently used to synchronize and reduce the interpolation error in OFDM systems including blind algorithms and wideband synchronization pilot signals transmitted intermittently in short time periods. The blind algorithms use a cyclical prefix instead of the pilot symbols to synchronize the OFDM system. The wideband synchronization pilot signals use an additional intermittent pilot signal to synchronize the OFDM system. The additional intermittent pilot symbol increases the pilot symbol overhead and is incapable of tracking any fast time variations in the channel. These methods when applied to multipath systems simply assume there is a single time and frequency offset to be estimated and do not directly consider multipath effects. These systems cannot synchronize to all of the channels simultaneously since each channel can have a different arrival time and frequency offset. Furthermore, these cannot adequately process signals having a delay or a Doppler spread.

Summary of the Invention

[0004] We have recognized that OFDM systems have a major problem in that implementations using pilot-assisted coherent modulation are highly sensitive to time and

frequency errors. To overcome this problem, a synchronization method for coherent OFDM systems with pilot-assisted linear channel estimation has been invented. In accordance with the principles of the invention , the receiver estimates the average channel estimation error by comparing the measured and estimated values of the channel gain on the time-frequency pilot points. The receiver then fine tunes its timing and frequency to minimize the estimated channel error. The minimization can be conducted in real-time using an initial coarse discrete minimization followed by a simple stochastic gradient tracking loop. This is well-suited to channels with both frequency and time dispersion and does not require any pilot data in addition to the channel estimation pilots.

Brief Description of the Drawings

[0005] Fig. 1 is a block flow diagram of a prior art pilot assisted channel estimation OFDM system;

[0006] Fig. 2 is an illustration of a signal containing pilot points and non-pilot points;

[0007] Fig. 3 is a block flow diagram of a pilot assisted channel estimation OFDM system according to the present invention;

[0008] Fig. 4 is a block flow diagram of the components of the phase rotation controller of Fig. 3 which provide the output to the Phase Rotation Across Time block of Fig. 3;

[0009] Fig. 5 is a block flow diagram of the components of the phase rotation controller of Fig. 3 which provide the output to the Phase Rotation Across Frequency block of Fig. 3; and

[0010] Fig. 6 is a block flow diagram of the components of an embodiment of the Low Pass Filter of Figs. 3 and 4.

Detailed Description

[0011] Fig. 1 is a block flow diagram of a prior art pilot assisted channel estimation OFDM system 100. The prior art pilot assisted channel estimation OFDM system 100 starts with a signal containing pilot symbols 102. The signal 102 may be transmitted wirelessly, by wireline or by another transmission media. The signal 102 initially undergoes time and frequency synchronization 104 followed by a fast Fourier transform 106. The initial time and frequency synchronization 104 can be preformed by setting time and frequency parameters as a function of the signal 102. The synchronized and transformed signal is input in to the pilot extractor and

channel estimator 108 and the coherent receiver 110. The pilot extractor and channel estimator 108 extracts the pilot symbols from the synchronized and transformed signal. The pilot symbols are arranged in a set of dedicated time and frequency points such that the receiver 110 can estimate the channel by some time and frequency interpolation from the pilot symbols as is known in the art. For example, Fig. 2 is an illustration of a signal containing pilot points and non-pilot points.

[0012] Fig. 3 is a block flow diagram of a pilot assisted channel estimation OFDM system 112 according to the present invention. The system 112 starts with a signal containing pilot symbols 102 that are produced at intervals. The intervals can all be of equal or substantially similar duration since no intermittent pilot symbols are required. The signal 102 initially undergoes an initial time and frequency synchronization 114. The initial time and frequency synchronization 114 is a coarse synchronization that is determined according to a discreet optimization. The initial time and frequency synchronization 114 only needs to synchronize the signal 102 to the point where intercarrier interference effects and intersymbol interference effects may be neglected. For example, intersymbol interference will be negligible when the receiver symbol timing is synchronized so that all signal paths arrive within the receiver cyclic prefix. Initial synchronization may not be required to be very accurate due to the inherent uncertainty in the true channel parameters and the large amount of computation necessary to determine the initial time and frequency synchronization 114. Channel changes occurring over time can be tracked and accommodated with a simple stochastic gradient tracking loop that runs continuously.

[0013] The initially synchronized signal then has phase rotation across time imparted to the signal to compensate for a channel frequency offset. The signal then undergoes a fast Fourier transform 106 followed by a phase rotation across frequency to compensate for a channel time offset. The signal having been phase rotated across frequency is then coupled into the pilot extractor and channel estimator 108 and the coherent receiver 110. The Phase Rotation Across Time 116 and Phase Rotation Across Frequency 118 blocks fine tune the signal timing and frequency to minimize the estimated channel error.

[0014] The pilot extractor and channel estimator 108 extracts the pilot symbols from the signal. The pilot symbols are arranged in a set of dedicated time and frequency points such that the receiver 110 can estimate the channel by some time and frequency interpolation from the

pilot symbols as is known in the art. A channel estimate $\hat{H}(t, n)$ is then output into the coherent receiver 110 and a phase rotation controller 120. The channel estimate $\hat{H}(t, n)$ can be defined as

$$\hat{H}(t, n) = \sum_{s=1}^{S} p_s \hat{H}_0(t_s, n_s), \text{ where } \hat{H}_0(t, n) = Y(t, n)/U(t, n) \qquad (1).$$

In equation (1), t is symbol period time, n is the tone frequency, S is the number of neighboring pilot points, p_s are interpolation weights, U(t, n) are the transmitted symbols and Y(t, n) are received signals. The phase rotation controller 120 uses the channel estimate $\hat{H}(t, n)$ to control the amounts of phase rotation that are imparted to the signal.

[0015] Fig. 4 is a block flow diagram of the components of the phase rotation controller of Fig. 3 which provide the output to the Phase Rotation Across Time 116 block of Fig. 3. The channel estimate is coupled into the phase rotation controller 120 to determine the phase difference between the last channel estimate signal, i.e., the channel estimate at time = k and the present channel estimate signal, i.e., the channel estimate at time k + Δk. This can be achieved by coupling the channel estimate into a unit symbol period time delay 122 and then coupling the delayed channel estimate along with the undelayed channel estimate into an element that determines the phase difference 124. The phase difference 124 is then averaged over the frequencies 126, e.g., a running total of the phase differences divided by the number of frequencies in the running total, and filtered by a low pass filter 128. The output from the low pass filter 128 causes a phase rotation in the amount of θ_T to be introduced. The term r[k] denotes the signal input to the Phase Rotation Across Time 116 block, where k is time variable. The output of the Phase Rotation Across Time 116 block r1[k] is equal to r[k] multiplied by $\exp(-j2k\theta_T)$.

[0016] Fig. 5 is a block flow diagram of the components of the phase rotation controller of Fig. 3 that provide the output to the Phase Rotation Across Frequency 118 block of Fig. 3. The channel estimate is coupled into the phase rotation controller 120 to determine the phase difference between adjacent frequency tones, or carrier frequencies, n and n + Δn, where n is the tone frequency and Δn is the frequency spacing between adjacent tones. This can be achieved by coupling the channel estimate into a single tone frequency shift 130 and then coupling the shifted channel estimate along with the unshifted channel estimate into an element that determines the

phase difference 124. The phase difference 124 is then averaged over the frequencies 126 and filtered by a low pass filter 128. The output from the low pass filter 128 causes a phase rotation in the amount of θ_F to be introduced. The term R[n] denotes the signal input to the Phase Rotation Across Frequency 118 block, where n is frequency variable. The output of the Phase Rotation Across Frequency 118 block R1[n] is equal to R[n] multiplied by $\exp(-j2n\theta_F)$.

[0017] Fig. 6 is a block flow diagram of the components of an embodiment of the low pass filter 128 of Figs. 3 and 4. The low pass filter 128 may be constructed with an inverting loop gain amplifier 132, an adder 134 and a time delay 136. The loop gain amplifier 132 inverts and scales an input signal for input into the adder 134. The output from the adder 134 is time delayed by the time delay element 136. The output of the time delay element 136 is the output of the low pass filter 128 and is provided as feedback into the adder 134. The low pass filter 128 may be constructed as shown in Fig. 6 or may be constructed from any other low pass filter.

[0018] The present invention may be applied to 2-way and multipath systems that operate in real time and may be implemented as software loaded into computers or other processors. The signals may include plural tones or carrier frequencies that each have an arrival timing offset and a frequency offset. The signals also have delay spread or Doppler spread. The channel estimation may be linear, quadratic or any other kind of estimation.

[0019] Although several embodiments of the present invention and its advantages have been described in detail, it should be understood that changes, substitutions, transformations, modifications, variations, permutations and alterations may be made therein without departing from the teachings of the present invention, the spirit and the scope of the invention being set forth by the appended claims.